but they potentially thread through discussions and affect interpretation.

The natural sciences

We enter the natural sciences first in terms of what they are not: they are not mathematics, in that they *do* study the material world, and they are not a spiritual worldview in that they study *only* the material world.

What, though, *are* the natural sciences? In your broad comparisons of natural sciences, human sciences, and history with mathematics, already you will have picked out several characteristics of this area of knowledge. Let us stand back a moment, though, just as we did with mathematics, and try to capture what we think of most when we turn to the sciences. What comes to our minds as they sweep over this broad field of physics, chemistry, biology, environmental science and their combinations?

Try the class activity. Do not turn the book to read the instructions until your whole group is prepared with paper and pen and you are given a collective go signal. The activity will take only a couple of minutes, though discussion of it will take rather longer.

Activity

Do not turn this book to read the instructions until everyone is ready and you are instructed to do so.

Identify in advance who will be the time-keeper, allowing 20 seconds for each of the activities.

1 Draw a hand.
2 Draw a house.
3 Draw one thing that you think represents mathematics.
4 Draw one thing that you think represents the sciences.
5 List as many words as you can that you think describe a scientist.
6 Bonus challenge: draw a scientist.

When everyone is finished, turn ahead to page 156 for questions for discussion.

The sciences and the search for pattern

It looked as though we were leaving mathematics behind as we entered the sciences, and indeed we are—up to a point. However, mathematics is an area of knowledge that always seems to come along to everyone else's party. If you glance back to the beginning of the section on mathematics, you will recall that it actually gets invited—largely because of what it brings along to make the party better. It brings its elaborate web of interconnected statements that turn out to be very useful in finding and talking about patterns that occur in nature.

And that's what the sciences are after: those recurring patterns, the regularities of nature about which they can generalize. The natural

sciences provide statements about all bodies falling to the ground...all plants...all chromosomes...all liquids...all ecosystems...They attempt to make generalizations about entire collections of things. The search for pattern has taken inquiring minds toward the neutrino of the subatomic world and to the stars of the universe, toward the study of inanimate crystals and to the study of living cells. Scientists search for the regularities and recurrent relationships that exist within the physical world, both to *describe* and to *explain*.

Of course, describing things in general terms is not the province of scientists alone. As you think back to earlier discussions you are already aware of how we use all our ways of knowing in classification every day (page 83): we associate and group our sense perceptions and our emotions with other similar ones; we use reasoning to make and apply generalizations; we use language to name the categories. You are also aware of some of the common errors in generalizing and classifying, and their potential use for manipulation (see Chapter 4). Sciences start with everyday critical thinking and develop it with care. As Albert Einstein once declared, making a huge generalization in the process, "The whole of science is nothing more than a refinement of everyday thinking."[20]

The periodic table is a diagrammatic representation of a general pattern that chemistry has found in the world; in visual terms, it describes the world. What would you say is the relationship between *description* and *explanation* in the natural sciences? Does the periodic table help you, as a science student, *explain* what is going on in experimental work or in the work treated in your textbook?

H hydrogen																	He helium
Li lithium	Be beryllium											B boron	C carbon	N nitrogen	O oxygen	F fluorine	Ne neon
Na sodium	Mg magnesium											Al aluminium	Si silicon	P phosphorus	S sulphur	Cl chlorine	Ar argon
K potassium	Ca calcium	Sc scandium	Ti titanium	V vanadium	Cr chromium	Mn manganese	Fe iron	Co cobalt	Ni nickel	Cu copper	Zn zinc	Ga gallium	Ge germanium	As arsenic	Se selenium	Br bromine	Kr krypton
Rb rubidium	Sr strontium	Y yttrium	Zr zirconium	Nb niobium	Mo molybdenum	Tc technetium	Ru ruthenium	Rh rhodium	Pd palladium	Ag silver	Cd cadmium	In indium	Sn tin	Sb antimony	Te tellurium	I iodine	Xe xenon
Cs caesium	Ba barium	La lanthanum	Hf hafnium	Ta tantalum	W tungsten	Re rhenium	Os osmium	Ir iridium	Pt platinum	Au gold	Hg mercury	Tl thallium	Pb lead	Bi bismuth	Po polonium	At astatine	Rn radon
Fr francium	Ra radium																

Learning science

Any student of science with a handy textbook has reason to feel grateful to language as a way of knowing. There it is—a solid and accessible book, a record of what many knowers have gained from their investigation of the world and passed on, publicly. It is not necessary for the next generation to start back at the beginning.

The science textbook, though, does not often give the moving picture of science in the process of creation: it is not the film but a

frame taken from it. Rarely does it give its pages to the past, to old science, as it teaches the current ideas and methods of investigation. You may be quite glad not to have a 10-volume set of books for your IB science course, books encompassing ideas proposed and believed along the way, but now left many, many frames behind. It is far more useful, as you learn science, to have the current frame. This current frame, of course, is already moving into the past as you learn. Unfortunately, though, the book's very solidity can sometimes lead students to believe that science is a body of knowledge that is true beyond doubt, and final.

In IB Diploma Programme experimental science, however, there is a counter-balancing emphasis: as a student you are learning not only the information but the process of science, not only "I know that..." but also "I know how..." With this emphasis comes a more balanced picture of science, not as a static body of knowledge but as knowledge in process, with continuing inquiry into the regularities of the world. Even though you are not a professional researcher creating new knowledge, in IB sciences you are learning something of how scientific investigation is done.

Activity: your own IB Diploma Programme science course

Divide up your class into smaller groups according to which IB science you are studying—physics students together, chemistry students together, and so forth. Subdivide if necessary to have groups of four or five. Have your science textbooks and notes handy to consult. In order to respond to the following questions, draw on your own IB Diploma Programme science course and your group 4 project, if you have already done it. First prepare group answers to the questions below, and then return to the full class group in order to report and compare.

The central question for your group to answer is this: *How do the natural sciences gain knowledge of the world?*

Try to deal, at a minimum, with the following questions:

- The natural world is immense, the current background knowledge is vast, and the concept of cause and effect is immensely complex. Where does a contemporary scientist or research group even begin?
- What are the relative roles of previous knowledge and current conjecture, or hypothesis?
- What makes a hypothesis a good hypothesis?
- Does your textbook tell you of any particularly ingenious experiments in science? Has your teacher described any in class?
- What does the researcher or the research group do with the results?
- How are other scientists, besides an individual researcher or a research group, involved in the creation of scientific knowledge? What does it mean to say, "Science is public knowledge"?

As you build up a collective class description of how science works to gain its conclusions, what are the features you find in common between your science courses? What are the differences between

Obsolete science: the condensed version

Conduct a mini research exercise, for a look at what does *not* appear in your current textbook. Work individually or in pairs, preparing a short report for the rest of your class.

Your report should give a brief explanation of the outdated science and attempt to answer the following three questions:

1. Why did people believe these theories?
2. Why do people no longer believe these theories?
3. Which of these obsolete theories is now irrelevant to science, and which has led to refined versions currently accepted?

- spontaneous generation
- maternal impression
- miasma theory of disease
- recapitulation theory
- caloric theory
- phlogiston theory
- anomalous water
- luminiferous aether
- steady state theory of the universe
- Rutherford model of the atom
- N-rays
- cold fusion
- flat Earth theory
- the Open Polar Sea
- alchemy
- astrology
- phrenology
- numerology

them? Scientific inquiry has common features but can take a variety of forms, with some clever problem solving along the way.

Creating science

In your IB Diploma Programme science course, you are learning about science—its methods of inquiry and its currently accepted information and theories. Imagine now the limits of science—that grey region of knowledge that hovers between what we think we know and what we're sure we don't know. In that fringe, the formulae and facts are not known, and are being sought with the same passion and determination as the proof to Fermat's Last Theorem.

Imagine that you're an *experimental scientist*. Your research team (very few scientists work alone these days) designs an experiment which you hope will be able to measure something you are seeking. Nobody has ever done this experiment before. If the experiment works, you will be amongst the very first humans to observe, in the laboratory, what you're hoping to observe. For example, will it be with this experiment that you'll be able to find experimental evidence that strings actually exist, helping to validate the beautiful mathematics of string theory?

Or maybe you're a *theoretical scientist*, working mostly with mathematics, writing equations with pencil on paper or, more commonly these days, performing complex mathematical calculations which you have arduously programmed into the computer. You have a pile of research papers on your desk, reprinted from venerable publications that only publish peer-reviewed articles. You also have some data on your desk which your experimental collaborator across the world sent you, rough data his team collected via extensive interviews and tests performed with pairs of identical twins. Your research team will analyse and try to explain data that nobody has managed to explain before. For example, what are the factors that cause one identical twin to develop Alzheimer's disease, but not the other?[21] Might your team be able to contribute to answering this question?

Or maybe you're a *field scientist*, going out and observing natural phenomena. Perhaps, like researcher Roman Dial, you're using a new method you've developed to propel yourself directly from tree to tree in the canopy of the Borneo jungle, and applying a new laser technology to help you map the jungle in a way never done before, using a technological extension of sense perception (see page 25). For the first time ever someone is able to map the canopy structures, and you're "investigating how they relate to the animals that live there".[22]

Just as in the distinction made in mathematics, all the scientists in the examples above are "basic" or "pure" scientists, in that they're not attempting to develop specific technologies. In very rough terms, basic science attempts to answer the question "why"—why does this happen like this or that?—whereas applied science attempts to answer the question "how"—for example, how can we do this or that more effectively or in a way that is less expensive?

The sequence of development can go either from pure to applied, or from applied to pure. The laboratory discovery of X-rays by Marie and Pierre Curie led to development of X-ray machines that enable the health of your lungs to be checked; Einstein's theory of special relativity led to knowledge about how to produce electricity using nuclear energy. In the other direction, the invention of the steam engine led to extensive knowledge of thermodynamics.[23]

Scientific method?

No fixed "scientific method" of a common sequence of steps unites all of these kinds of natural scientists, working in very different ways on very different problems in very different aspects of the natural world. Scientific papers are written in a certain order—the same order in which you are asked to write lab reports—but that is not really the way that discoveries are made or explanations are created. Hypotheses may be generated in many different ways, some of them involving creativity too elusive to grasp.

Research exercise

Divide up your group to investigate the following examples of quite different "methods" of creating scientific knowledge.[24]

- serendipity and methodical work: Roentgen's discovery of X-rays
- detailed background and dreamlike vision: Kekulé's discovery of the structure of benzene
- idealized models and mathematical calculations: discovery of band structure in solids
- exploration and observation: Von Humboldt and the biogeography of ecosystems
- hypothetical-deductive method: Edward Jenner and the discovery of smallpox vaccine.

Whatever the specific method of the natural scientist, however, the broad approach outlined within your Diploma Programme science courses still prevails—combining background knowledge, creative conjecture, testing, and finally publishing. However generated, the hypothesis must be tested. If it is repeatedly found flawed, it is laid aside—though, even if it "fails", it may have led to new information coming to light in the process of testing. It may, otherwise, be modified for further testing. If testing seems to confirm the hypothesis, it is not accepted until it has been tested further—ideally rigorously and repeatedly, with the possibility of other scientists also testing it, directly or indirectly, if it is relevant to their own work.

Into which of the three categories above—experimental scientist, theoretical scientist, or field scientist—would you put the scientist you are about to meet? Read the following interview with a nuclear physicist—who is an IB graduate. Consider as you read what he is saying about aspects of science in the process of creation: imagination, testing, models, metaphors, the role of technology, and common features across sciences. The interview is followed with some further questions.

Stereotypes?

Discussion on your class activity (see page 152)

Drawings 1 and 2: Compare within your class your drawings of the hand and the house. Are they very similar to each other? If so, why do you think this is so?

Students from all around the world, with hands that move into many positions and home dwellings of many different kinds, tend to draw hands and houses in almost exactly the same way. (This general tendency may, of course, not be the case in your own particular group.)

Drawings 3 and 4: Compare your drawings. Do some images or symbols recur? What characteristic features of mathematics and the sciences do your drawings reflect?

Wordlist 5 and drawing 6: Share your words and compare your drawings. What impressions of the scientist emerge from the group? Is there any indication of one of the common stereotypes—a middle-aged white male in a lab coat, with glasses, wild hair, and the slightly crazed look of a mad inventor?[25]

Are there any other recurrent features in your verbal and visual impressions?

How would you find out whether these general images of the scientist are sound generalizations or stereotypes?

Science, technology, and the subatomic world

Interview with Dr Patrick Decowski, IB graduate 1991

Patrick Decowski has an MSc in Nuclear Physics from Utrecht University, the Netherlands, and a PhD in Nuclear Physics from the Massachusetts Institute of Technology. He is currently a researcher at the University of California at Berkeley.

Would you please explain what you are researching?

My research focuses on a subatomic particle called the neutrino, one of the particles emitted in radioactive decay. The neutrino does not have electric charge and very little mass. We do not know the exact mass yet, but it is for sure 100,000 times less massive than the electron, the lightest particle of "ordinary matter". The neutrino is copiously emitted by the Sun, but very difficult to stop: more than a hundred billion neutrinos pass unhindered through your thumbnail every second! The neutrino is still one of the least understood subatomic particles and many current and future experiments aim at unravelling its mysteries.

I work on a project called KamLAND. The experiment is located in an old zinc mine in western Japan. The experiment consists of a large, 18-metre diameter container filled with 1,000 tonnes of liquid scintillator (essentially baby-oil with a fluorescence) that is viewed by 1,800 light-sensitive detectors. About 40 times per second particles interact with the liquid scintillator and give off light flashes that are recorded by the light sensitive detectors and stored for later analysis. It turns out that the vast majority of the light flashes we see come from background events. Using elaborate computer algorithms, we can identify particle light flashes coming from neutrino interactions with the liquid scintillator. Our project has been very successful; based on our measurements we have gained a much better understanding of the properties of the neutrino.

When we discuss the natural sciences in TOK class, we talk about it as a study of the natural world—the physical or material world. If what you are studying is a particle far, far, far too small to see, are you still studying the physical world? Should we change the way we talk about science?

The neutrino (or any other subatomic particle for that matter) is indeed far too small to see directly. We always study these particles through their interactions with other particles, "amplifying" their presence and inferring their existence. Also, once you get to subatomic length scales, you are firmly in the quantum world and you can no longer talk about particles being objects of a defined shape or form.

At the same time, although we do not see these particles, they are part of the physical world. We can make accurate predictions of what we expect to see and then perform the experiment to test the hypothesis. Indeed, one of the great triumphs of particle physics was when the quark model was developed (quarks are the building blocks of protons and neutrons that make up the atomic nucleus). The quark model not only describes how protons and neutrons behave, but it also predicted the existence of a certain short-lived particle. When physicists looked for this particle, they found it. The material world is not limited to entities that we can see or touch. As a matter of fact, the vast majority of our material world turns out to consist of vacuum, with only every now and then a tiny particle that determines the properties of the material. Additionally, in recent years we have discovered that we interact and see only 4% of the total mass of the universe! 26% of the mass is so-called "dark matter" and the other 70% is "dark energy". We currently do not understand this stuff and it is subject to intense study.

Models, from what you say, really help you to conceptualize particles and their relationships. Do you have other ways of conceptualizing them, perhaps using metaphors?

It really depends on what questions you want to ask. Different theories work as different metaphors in science. To give an example, when studying properties of a gas, the gas particles (which can be single atoms) can be thought of as being little billiard balls. It is not that they are really little billiard balls, but that metaphor allows us to make certain predictions for the gas that are validated by experiment. But one must not confuse that metaphor with reality. When looking at the gas particles at a smaller scale than the overall gas (such as what I am doing in neutrino physics), the billiard ball metaphor breaks down and we really have to think in quantum-mechanical terms. It turns out that viewing particles as waves is a much better

metaphor at those length scales. Even the mathematics that sits underneath all of our theories can be seen as "quantitative metaphors". Just because there is currently a correspondence between these equations and the physical world, does not mean they are one and the same.

What is the role of computer modelling in your research? Can you do "experiments" within a computer?

Computer modelling is extremely important in most branches of science nowadays. In subatomic physics it is particularly important. Most experiments cannot be interpreted without a significant amount of modelling, to understand both the behaviour of the detector and the physics being studied.

Doing experiments in computers has also become very popular, because specific hypotheses can be tested relatively quickly for their consequences. A hypothesis with a set of starting conditions can be stepped through in time inside the computer and then tested for violation of specific physical laws (such as energy conservation) and discarded if it does violate some important law or does not match observation. The great advantage is that computer simulations allow us to study theories that are otherwise hard to test. The modelling helps in fleshing out the theory, but the computer predictions have to be compared with real, physical world experiments.

Computer modelling has become a very important branch in physics. These types of modelling are not done only in nuclear physics and meteorology, but also in astrophysics, biophysics, climate studies, and so on. Computer modelling really has revolutionized the way we do research and the current generation of scientists spend considerable time in front of computer screens.

Einstein has been quoted as saying that imagination is more important than knowledge. In your kind of scientific research, what is the role of imagination?

I think that what Einstein meant was that you have to have an open mind and think out-of-the-box. It is extremely important to have imagination in physics. When seeing some unexpected effect, you have to use your imagination to try and understand what you are seeing. Is it a detector effect? Is it due to the environment? Could it be new physics? This is usually where we spend most time, in interpreting the data. You try to vary some accessible parameter in the experiment and ask, "Is the effect changing?" The imagination is necessary for coming up with hypotheses, but this is always followed by testing.

Why do you find your research so interesting?

I have always had a fascination with how things work. Over time I realized that what is even more amazing is that nature itself works so well and that I wanted to understand it better. Certain "themes" come back in areas that superficially do not have anything to do with each other. Why is it that ocean waves and light rays can behave in similar ways? Why do the same equations describe a mechanical and an electrical oscillator? There are similar "themes" and symmetries at the very smallest particle level. This led me to become interested in subatomic particles and the neutrino is one of the least understood and most fascinating particles.

The fundamental nuclear physics that I do is in some sense similar to what astronomers do when they look at stars. They look upwards at the large scale, whereas I look downwards at the very small scale. My research does not have any direct application– just like knowing how stars shine does not have any obvious application. We are studying it purely for the knowledge and trying to understand what is behind it. This is in many respects similar to the reasons why people enjoy art. Science is captivating.

Questions for discussion

1. Patrick speaks of "our project" and "our measurements". In a field such as his, would you expect scientists to be working alone or in research groups? Why?
2. What is the role of technology in his group's experiments? Does your own science course depend extensively on technology?
3. What does he say are the roles of imagination, models and metaphors, and testing? Do his comments also apply to the science you are studying for the IB?
4. He describes both the correspondence test for truth and the coherence test for truth (see pages 100–101) in action, though without giving them these names. What is the role of each in his experiment? In your most recent experiment for your science course, what truth test were you using?
5. From his description, what resemblances do you find between scientific research and detective work?

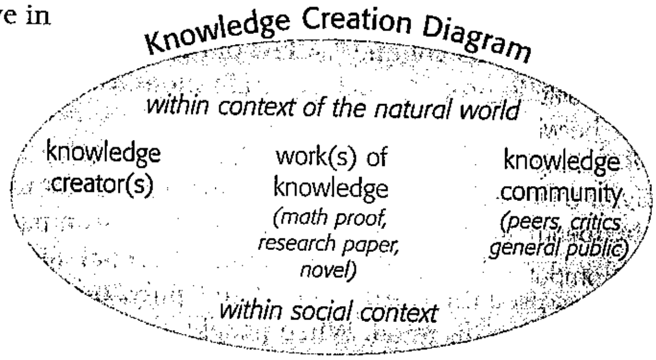
The natural sciences: the whole picture

The knowledge creators

"Why is it that ocean waves and light rays can behave in similar ways? Why do the same equations describe a mechanical and an electrical oscillator? There are similar 'themes' and symmetries at the very smallest particle level."

Patrick Decowski echoes in this interview on research in physics a fascination with patterns so often also expressed by mathematicians. You may recall the words of Andrew Spray (see page 144), speaking of why he so loves mathematics: "it is the patterns, the searching for them and the joy of discovering them, that captivate me most." In the natural sciences, the search for pattern takes a form different from that in mathematics, and gives a different kind of justification for the knowledge claims it brings back from its search. Yet, for many minds, it exerts a similar magnetic pull.

The kinds of pull that draw scientists into this area of knowledge, however, are as various as the individuals. As one Nobel Prize winning scientist said, surveying his colleagues, "Among scientists are collectors, classifiers, and compulsive tidiers-up; many are detectives by temperament and many are explorers; some are artists and others artisans. There are poet-scientists and philosopher-scientists and even a few mystics. What sort of mind or temperament can all these people be supposed to have in common?"[26]



The picture of "the scientist" becomes even more fuzzy in contemporary science because our knowledge creators work in teams—teams of physicists, chemists, biologists, environmental scientists, and increasingly, interdisciplinary teams of them—experimenting in laboratories, observing in the field, or working in offices connected to very powerful computers.

The scientific work

The knowledge creation diagram, by now familiar to you, moves us on from the scientists to their work, of which we are already gaining an idea through the examples we have seen.

Science, as we have observed repeatedly, is a public area of knowledge, with work contributed to a kind of living public archive through the channels accepted within science—the published paper, the conference paper, and to an increasing extent an online computer archive of what work is in progress.

The new assertions published by natural scientists are usually not very dramatic—rarely the revolutionary discoveries that make the news or dramatic fiction. For example, one of the authors of this book, Lena Rotenberg, spent three years of her life as a research physicist studying a polymer that had been modified by a chemist. She measured its properties as a function of its temperature, and then had to explain why the graph she obtained did not comply with the expectations of a model presumed to work for similar

samples. She had to come up with an alternative explanation in order to publish the paper—something like "this material appears to be X, but it's behaving like Y, which might be due to factors (a), (b) and (c)". When she finally had the "aha!" moment which enabled her to explain the data, it was a very exciting feeling: nobody had ever gone to the fringe with that particular material before. In the context of the edifice of science hers was a very, very minor result—she hammered a small nail in a small room in a forgotten hallway on the side of a very huge house (the house is a metaphor for the theoretical construct) of solid state physics. But that's how the majority of the basic natural sciences are developed—with small, particular results cumulatively added to each other in an international, collaborative effort. Most scientific theories are supported by hundreds of thousands, if not millions, of such small observational nails, hammered into place by scientists over many centuries.

More dramatic works achieve the kind of generalizations that the natural sciences seek, the identification of regularities. Every so often a scientist manages to identify a pattern in the specific, minor results published by large numbers of scientists—manages to see a causal connection—and can show that "if P, then Q". An example is Boyle's law, mathematically expressed as "PV = constant at a fixed temperature", which asserts that "If a rarefied gas is kept at constant temperature, then there is an inverse relationship between its pressure and its volume." A few of the research papers produced by scientists do propose such generalizations, called scientific laws.

Major scientific work: scientific theories

Even more seldom than laws, natural scientists produce scientific theories, the overarching constructs that encompass and explain many laws. It is sad that the popular fictional detective Sherlock Holmes used the word "theory" so lightly to refer to any conjecture that came to his mind. When people use the phrase "it is *just* a theory" in regard to a scientific theory, they are discounting a tremendous amount of evidence, as we mentioned above. It is also confusing that the result of a mathematically-based work with no experimental evidence (such as string theory now, and quark theory until quarks were finally detected a few years ago) uses the same name.

"Music is the favourite art of the scientist. And so it should be. It allows us to see new worlds with our eyes closed."

John Polanyi, Nobel Prize in Chemistry, 1986.[28]

The best scientific theories have several characteristics.[27] They:

- encompass scientific laws, which are deducible through them
- make existential or factual claims, such as "electrons exist and have a charge of minus one", or "ideal gases consist of a very large number of atoms with negligible size, in random motion, which collide elastically with one another"
- refer to unobservable entities or properties that stand behind the measurements we make: for example atoms, natural selection, the curvature of space, strings
- are interrelated in such a way that they explain not only a particular law or phenomenon, but whole ranges of each—such that apparently diverse laws or phenomena can be explained within a common framework

- provide an enormous predictive power (including phenomena which were previously unknown).

Scientific explanation: your own natural science course

Class activity

Form groups within your class, as you did earlier, according to the particular IB Diploma Programme science course you are studying—chemistry students together, and so forth. If most in your group study the same science, break up into subgroups of four or five. It would be very useful to have your science textbook and class notes to consult.

First, answer the following questions within your group. Then, as a class, exchange what you have found and compare your understanding of how science seeks to explain.

1 From your own science course, find examples of each of the following:
   a *a scientific hypothesis*: a conjecture, based on evidence, interpretation, and imagination of a causal relationship.
   b *a scientific theory*: an explanation based on evidence of causal relationships found in the world, which accounts for phenomena already observed and provides a framework, shared by the scientific community, for further investigation. Can you identify theories used within the science you are currently studying? Do they possess the characteristics of the best theories, outlined above?
   c *a scientific model*: an image or three-dimensional object that represents things or processes that we believe to exist in the world and that selects some relevant features to clarify relationships.
   d *a scientific law*: an expression of a causal relationship established on the basis of evidence and tested sufficiently extensively that it is considered reliable and spoken of as true.
2 Do these four elements of scientific knowledge describe the world or explain it? What is the relationship between them?

Description and explanation may be seen as different kinds of patterns that scientists search for in nature. The description is the map: "this is what it looks like". The explanation, though, involves something we do not perceive through our senses but construct with our minds: cause. We do not *see* cause. We *infer* it from repeated correlation of events, tested until we are confident of the nature of their connection. In practice in science, the two kinds of pattern are completely interconnected.

Of all the patterns that science has discovered in recent decades, perhaps the ones that have been absorbed most strikingly into the awareness of the general public are fractals—not only because they represent a breakthrough in science but because they please our eyes.

Fractal patterns: mathematics, science, technology...and beauty

Interview with Dr John Dewey Jones, P.Eng., School of Engineering Science, Simon Fraser University, Vancouver

As an engineer, did you first become attracted to fractals through the mathematics or through the technology?

I was inspired to start creating fractals by Dewdney's "Computer Recreations" article in the August 1985 *Scientific American*. Creating fractals was computationally intensive by the standards of that time, but as an automotive engineer working for General Motors, I had access to one of the fastest supercomputers in North America (roughly as powerful as a modern digital watch). It was very exciting to watch the complex organic patterns of the Mandelbrot set emerge on the screen, the image building up line by line; and to add to the excitement was the risk that someone from GM management would come by and notice that I wasn't designing cars.

Frosted branch

They are, as you say, "complex organic patterns". Are they really simply the results of equations fed into a computer?

Despite their dissimilar appearance, both "frosted branch" and "diatom" show the results of repeatedly applying the transformation

$z_n = z_{n-1}^2 + z_0$

to a range of complex numbers z_0. In each case, starting with a small complex number z_0, we square the number, add the original number to the result, and repeat until the absolute magnitude of the result exceeds 2. The differences between the two pictures all stem from a small difference in the complex numbers we started with.

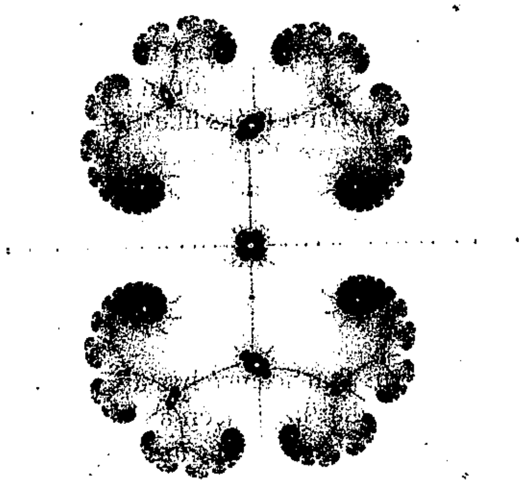
These pictures, like all computer pictures, are made up of a large number of pixels—the phosphor dots making up the computer screen. Every dot in the picture corresponds to a single complex number—its position on the horizontal axis corresponds to the real part of the number, while its position on the vertical axis corresponds to the imaginary part. We assign each pixel a shade of grey depending on how long its magnitude takes to grow greater than 2.

What kinds of patterns do you see yourself within your mathematically generated images?

The image "diatom" looks symmetric, but if we look more closely, we see that while the lower half is indeed a mirror image of the upper half, the left and right halves of the image are not perfect opposites—the lines separating the left and right halves both trail off to the right, for example. We also notice that these lines are studded with small blobs. Each blob, if we magnified it, would turn out to be a complete figure as complex as "diatom" itself—and each of these diatoms would in turn contain blobs, which, if magnified...

Despite the almost graph-like symmetry of this figure, it does rather suggest a section through a cauliflower floret. This is a recurrent characteristic of fractal images, and we see it again in "frosted branch". Just as frost, formed by the simple physical process of freezing, can produce intricate, plant-like forms, we see here that the even simpler mathematical process of iteration can mimic both frost and organic plant life.

This, perhaps, is why fractal images fascinate and intrigue us—by showing the immense complexity and beauty that can result from a few simple rules, they hint that the world's complexity and beauty may also be the product of laws that we can discover and comprehend.



Diatom

Fractal images and chaos theory: some characteristics of science

The receding, self-duplicating shapes of the fractal image give a pattern that emerges from chaos theory—a theory with a particularly catchy name. Paradoxically, the theory of chaos is in many ways a theory of order: it reveals a new kind of pattern within the turbulence of nature, with limits on the degree to which it can be predicted. In its development, chaos theory offers a good example of some of the characteristics of science at work.

For one thing, natural scientists do not make their observations randomly, but purposefully seek pattern where the predominant theory suggests that it would be most fruitful to do so. In doing so, they have the advantage of being able to research and communicate within a common conceptual framework of theories, models, laws, and vocabulary. However, they also have the disadvantage of being directed away from patterns not illuminated within that theoretical framework. "The phenomenon of chaos could have been discovered long, long ago," commented one scientist involved in its recognition. "It wasn't, in part because this huge body of work on the dynamics of regular motion didn't lead in that direction."[29]

For another thing, there may often be a great difference between the way that *science* accepts change and the way that *scientists* do. After all, "science" is an abstraction, representing a vast base of provisionally-accepted knowledge and procedures. When we say that "science changes its mind" we are using an image, personifying a system of knowledge that, actually, has no mind to change. Scientists, however, do have minds to change—and like other people often have difficulty doing so, especially after having worked for a long time with one familiar way of perceiving things. In the early days of chaos theory, its proponents faced considerable resistance, verging at moments even on hostility.[30] Understanding and acceptance of the new theory was slowed, too, by its having no home in any particular discipline but instead crossing many disciplines, being applicable to, for example, weather patterns, fluid dynamics, populations in biology, and electrical activity of the heart.

Chaos theory, moreover, illustrates the intimate relationship between developing science and developing technology. It was the amazing computational power of the computer that enabled scientists to see the considerable long-term consequences of tiny changes in initial values of the variables. This sensitive dependence on the starting data has been dubbed "the butterfly effect", another very catchy name which captures the sense of tiny differences that can add up to affect the course of events in the future. Unless we have perfectly precise knowledge of every influence in the present, no matter how minute, our predictions become increasingly off the mark as we cast them farther into the future. And such omniscience is quite beyond us. Nevertheless, the computer technology that exposed the limits of prediction simultaneously revealed patterns within the unpredictable. "The system is deterministic," observed one of the early chaos scientists, "but you can't say what it's going to do next."[31]

The butterfly effect

The butterfly effect is the particularly charming name given to the idea that tiny, unmeasurable events can accumulate to cause major ones. Even the breathing of a butterfly in the Caribbean contributes to conditions that can result in a hurricane in another part of the world.

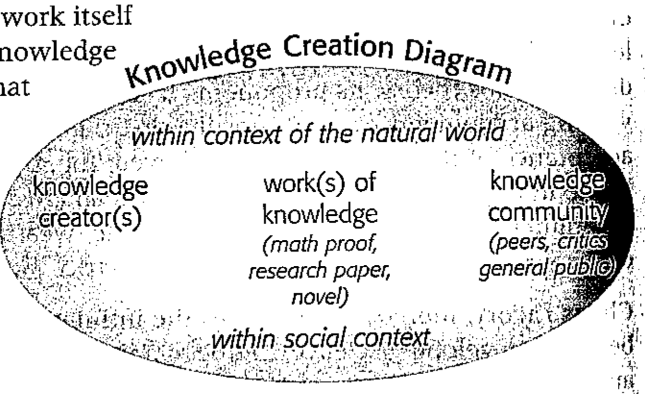
In addition, chaos theory demonstrates graphically the idea of pattern that recurs through many areas of knowledge—through mathematics in the patterns created rationally by the mind, in the sciences in the patterns found in the world of sense perception (often using mathematics and technology), and through the arts in the patterns created from all the raw material of experience. In all of these areas, their practitioners are apt to have moments of pure admiration: "It's beautiful!"

Finally, chaos theory, like many other theories in science, also has its effect on the public, in the way that it influences how we understand the world and speak about it. It is tempting to apply the idea of the butterfly effect, as novels and films have, to an idea that probably came up in your class discussion of why you are *here, now*: if it weren't for that one small event in your life, it might have been otherwise.

Natural scientists, their work, and the world: truth?

A scientific work may be beautiful, and may be persuasive. But is it true? In the knowledge creation diagram, the natural world is the context within which we all live, but for natural scientists it is also their subject of study. They identify patterns not for their beauty—though they may appreciate it—but for their truth.

Consider the diagram now with this question in mind: How do natural scientists test for truth? With your own personal experience of IB science, the class activities of this chapter, and the supporting text and interviews, you should by now be seeing this diagram as a schematization of a living process. As scientists test for truth, are they checking exclusively the connection between the work itself and the natural world, or between the work and the knowledge already shared with the knowledge community? To what extent is the knowledge shared between the creators and their peers both a help and a hindrance, in a way characteristic of the interplay of mind and eye in sense perception?



As you consider the way the natural sciences work and the kind of knowledge they give, what other relationships do you begin to draw between the components of this diagram?

How do scientists evaluate their work, or test it for truth? Read the following quotation from Peter Medawar, who won the Nobel Prize for Medicine in 1960, and who has written extensively to provide the general public with an understanding of the natural sciences:

> Scientific theories (I have said) begin as imaginative constructions. They begin, if you like, as stories, and the purpose of the critical or rectifying episode in scientific reasoning is precisely to find out whether these stories are stories about real life. Literal or empiric truthfulness is not therefore the starting-point of scientific enquiry, but rather the direction in which scientific reasoning moves. If this is a fair statement, it follows that scientific and poetic or imaginative accounts of the world are not distinguishable in their origins. They start in parallel, but

> diverge from one another at some later stage. We all tell stories, but the stories differ in the purposes we expect them to fulfil and the kinds of evaluations to which they are exposed.[32]

What "kinds of evaluations" do the stories of science face, and how do they involve the components of the knowledge creation diagram?

Correspondence test for truth

The correspondence test for truth, you will recall (see page 101), demands that the statements we make correspond to what we observe in the world. To test, scientists examine the world and find evidence either directly through sense perceptions or via technological extensions of the senses.

They must offer evidence in the form of replicable results. It is essential that every time something is measured, the same result be obtained. For example, distilled water should boil at 100 °C at sea level no matter where in the world we are, and no matter when we make the measurement. Every time a scientist observes a phenomenon the results should be either the same or justifiably different (for example, we can predict the boiling point of water at different altitudes[33]). Mitosis occurs with the same steps in cells all over the world. If one scientist performs an experiment in Germany, a colleague in Tanzania should be able to replicate the results.

How much evidence is enough evidence for declaring a statement of the natural sciences true? As you will recognize from descriptions of how the sciences work, their statements are never assuredly true forever, in the manner of mathematics. Indeed, by the very nature of scientific generalization and inductive reasoning (see page 76), it is possible to refute statements—*falsify* them—but not to prove them true. Scientists work with probabilities and accept as true (for now) the conclusions best supported by the evidence available at the time. They call this *provisional* truth.

Coherence test for truth

The coherence truth test for truth (see page 100) demands that the statements we make be consistent with each other. To test, scientists look not at the world but at the knowledge claims themselves and, as mathematics does, examine them for consistency, freedom from contradiction.

Not only should the observations and measurements be consistent with each other, but, on a deeper level, the explanations that they give about phenomena should also be consistent with each other.

Yet how much consistency with each other do the sciences demand for explanations to be accepted? Sometimes the sciences replace older theories within which contradictions have appeared with new ones which integrate all the evidence harmoniously. However, at other times they accept more than one version, each internally consistent but not consistent with the other, as each has its area of applicability.

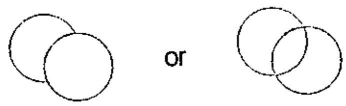
Consider the following two sets of theories, evolving through time.

Biology	Physics
1 spontaneous generation	1 Newtonian mechanics
2 Lamarckian evolution	2 Einstein's theory of special relativity
3 Darwin's theory of evolution	3 quantum mechanics

In the first set, spontaneous generation was shown not to happen—new theories replaced the old. In the second set, we continue to use Newtonian mechanics most of the time, to explain what happens in human size ranges and at speeds at which we usually move.

Which of the two models of the natural sciences shown is applicable?

The natural sciences



New replaces old through falsifying, | New coexists with old.

The hope expressed by some natural scientists is that, with progress over time, the sciences will eventually reach a grand unified theory, as all scientific theories become merged into an overarching explanation that brings them all into harmony.

Pragmatic test for truth

The pragmatic test for truth (see page 101) demands that the statements work in practical terms.

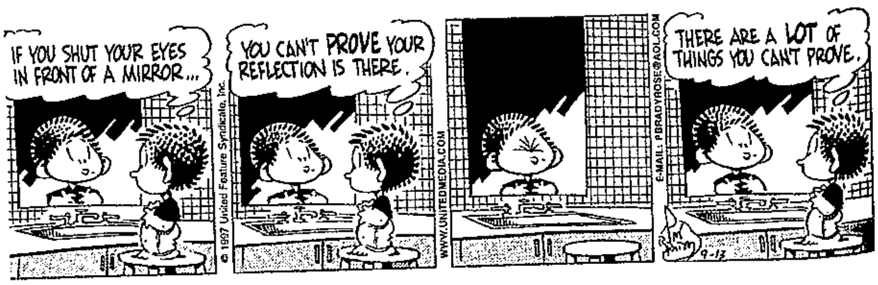
The pragmatic truth test is also central to the natural sciences. We accept certain assumptions without empirical proof, like axioms, because they happen to work. For example, we *assume* that nature is regular and understandable.

We *assume* that Ockham's razor, also known as the law of parsimony, holds true: when we have two equivalent theories, we choose the one that is conceptually simplest, with the "most economical conceptual formulation". Phlogiston, for example, was not necessary to describe heat, and therefore the concept was discarded.

We *assume* that the laws of physics we develop are applicable all over the physical universe.

We *assume*, to an extent, that theories that are mathematically beautiful and symmetric are more likely to be true, and search very hard for experimental evidence to confirm them. We did that with Einstein's theory of general relativity and with Gell-Mann and Nishijima's theory of quarks, and we are now trying to find empirical evidence for string theory.

For many years we *assumed* that the scientific observer could stand outside the experiment and not affect it, but Heisenberg's uncertainty principle demolished that illusion. When we study the realm of the atomic and subatomic, we affect our data by the very act of trying to measure it.



The axioms of science, despite their occasional failure, serve us well. Look around you and realize how many results of science surround you, and how much you trust them without even thinking. You hop on an

airplane, get in a car, drink water purified by the city, and take medicines your doctor prescribes, trusting that all the science behind them will work.

Is the explanation that works necessarily true in an absolute sense? No. But at least for now…it works.

The natural sciences and their critics

As has been evident in these pages, criticism is an essential part of the process of the sciences, as works of the natural sciences are replicated and reviewed by peers. As in mathematics, it may be only the specialists within the particular field who understand and examine effectively the new work, but in principle the knowledge is open publicly to all.

As in mathematics, the sciences also have critics—scientists or philosophers—who examine the way the entire area works and the problems that it encounters in making knowledge claims. Like mathematicians, natural scientists have had their moments of distress on realizing the imperfections in the claims their area might make to truth. *Yet it is only if you expect to be perfect that you consider imperfection a failure.* The contribution of many critics of science has been to give science more realistic expectations than it had of itself at the beginning of the 20th century.

Criticisms have been various. Some have stressed the fallibility of sense perception, even when extended by technology, and the fallibility, too, of indirect technological observation. Others have stressed the limits of inductive reasoning, with the goal of making accurate generalizations about *all* phenomena limited by having access in study only to *some*; counter-evidence will overturn or "falsify" an inductive generalization. Still others have cited human fallibility in experimental methods, and the fact that scientists replicating flawed work may also, influenced by their expectations, replicate the flaws. More broadly, critics have pointed out the bias that comes with theory and observation; as in everyday life observation, scientists look where they expect to find and, when they see, interpret with the bias of previous knowledge. Finally, critics have emphasized the implications of some significant findings in science: the uncertainty principle, which tells us that the very act of observation may in some circumstances affect the thing that we are observing, and that we cannot expect to remove our own presence from an experiment; and the butterfly effect of chaos theory which emphasizes that the inevitable limitations of our knowledge of all things in the present affect the accuracy of our predictions into the future. All of these criticisms have been illuminating. And science, with a better understanding of itself, gets back to work.

Less thoughtful criticisms of science have come from other sources, such as pseudo-science. Lacking sufficient evidence to have their claims accepted as science, pseudo-scientists have often accused the "scientific establishment" of being close-minded or even prejudiced against them. Admittedly, the inertia of accepted theory and the difficulty scientists may have in reconceptualizing their explanations

often do create resistance to new ideas. However, legitimate claims find their way through the resistance—by means of tested and replicable statements, based on evidence. These pseudo-science cannot provide.

How can we recognize pseudo-science? One commentator, a professor of physics, proposes seven "warning signs" of pseudo-science—while recognizing that "even a claim with several of the signs could be legitimate".[34] His warning signs can be summarized as follows:

1 The discoverer bypasses peer review to go directly to the media.
2 The discoverer claims that the scientific establishment, possibly as part of a larger conspiracy, is trying to suppress his work.
3 The evidence is extremely hard to detect.
4 The evidence takes the form of individual observations or stories, not able to be generalized.
5 The discoverer claims that the knowledge is ancient and hence more credible.
6 The discoverer has worked alone.
7 The discoverer needs to propose modification to the laws of nature in order that his findings be credible.

In trying to distinguish pseudo-scientific claims from the claims of the sciences, we affirm once again a basic principle of this book: that critical thinking requires a mind open to alternatives yet concerned to sift through them for the version that is the best justified. As critical thinkers, we expect to identify multiple perspectives, recognize their contribution to an understanding of the whole, and not reject them summarily. A contemporary emphasis on knowledge as culturally constructed and variable helps us see the significance of difference perspectives. However, the fact that there are many perspectives on something does not imply that all of them have equal claim to be accepted. Think back to the maps of the world that you drew at the beginning of this book. All of them were equally good as records of what you carry in your mind. But they were not all equally good as records of the world.

We end these pages on the natural sciences with some reflections and questions for you, as a member of the public affected by the process and products of this area of knowledge.

In what ways does the general public—like you and your family—benefit, directly and indirectly, from the products of scientific research? Do you consider there to be effects that are not beneficial? If so, where does the responsibility, if any, lie for reducing ill effects?

In what ways are you personally affected by "scientific thinking"? In what ways do you think your society absorbs or resists the knowledge given by science?

In the natural sciences, the creators of knowledge and the critics of that knowledge are peers, sharing findings publicly within their own knowledge community—a community not geographically defined but crossing borders as readily as the exchange of knowledge.

This community has a set of values. What would you, as a student of science, identify as the values that are prized by the sciences in their way of working as a public area of knowledge? What code of conduct would you expect natural scientists to follow in their treatment of their work and each other? Why is fraud in the sciences considered to be such a serious breach of professional conduct?

The knowledge community of the sciences, united conceptually but fragmented geographically, consists of people who work and live in towns and cities, within countries and regions which affect their work and are affected by their work. Whether the sciences are supported and funded and by what organizations, whether they are controlled and by what organizations—these issues have an immense impact on science and scientists. Their work and their knowledge do not exist in isolation from their human context.

Read now the following interview on the knowledge community of the sciences, set within a social community. Dr Maarten Jongsma is a distinguished researcher—and a former IB student.

Respond to the questions that follow this interview. They may give you some thoughts—and possibly a presentation topic—to take away with you.

Science in its social context

Interview with Dr Maarten Jongsma, IB graduate 1980

Maarten Jongsma has an MSc and PhD (1995) from Wageningen University in the Netherlands. He is currently working at Plant Research International. He built his own research group focusing initially on the application of protease inhibitors for insect resistance and later including work on metabolic engineering of plants for insect and disease resistance. He has coordinated multiple national projects and two large ones for the EU, and is currently managing international collaboration with China.

One of the stereotypes of science is that breakthroughs are made by the lone genius, the solo scientist following his own brilliant idea. How accurate is this picture of how results are achieved in science?

In my field of work (plant genomics and genetic engineering) the papers that have major impact and end up in *Science* and *Nature* are often the result of hard work and collaborations across different disciplines. A good example is the sequencing of the first plant genome (*Arabidopsis*). Another one is a recent paper in *Science* in which we describe how plants become attractive to predators of insects based on specific emitted volatiles. These results are considered important hallmarks, but to some extent they are expected, and part of the original hypothesis on which the grant money was obtained. To obtain the result your main task is to be a good manager to execute it and to arrange all the right collaborations if you have only part of the expertise.

Yet at the same time I can also give examples of the stereotype. Those results are never planned or expected and the result of inspiration based on unexpected results and requiring lateral thinking. Usually, however, the inspiration is immediately shared and tested with colleagues and incorporated into the usual line of research, requiring again the work of many to achieve the final top-rated paper.

Does it make sense to talk about the social context of scientific research being a "scientific community" beyond the immediate research group?

Certainly scientific research extends well beyond the immediate research group. Research would not happen without the consent of many due to the large amounts of money which it consumes. Many scientists in higher positions are constantly working on obtaining grant money and the proposals are nearly always peer reviewed. Furthermore, one of the most important and honourable platforms for the

research produced is the scientific conference. Excellent papers are invited for oral presentations leading to the further dissemination of the results. Also there is a lot of moving around of scientists. Often your best graduates will go to your competitor.

In research over which there is public controversy, such as your own work in genetic modifications, do you see the scientist as having any special responsibility to the broader society beyond the scientific community?

Certainly I believe that one has a social responsibility. However, I feel that scientists are often considered highly suspect due to the active propaganda issued by NGOs. My interest in participating in the debate is often to demonstrate the good that the technology can bring. An exclusive focus on the potentially bad sides with the aim of eliminating the technology altogether is a dead-end road, which, in my opinion, will harm society. I cannot avoid taking a stand in that debate.

What are some of the good sides?

Developing countries like India and China, representing nearly half the world population, have embraced plant biotechnology as one of the major ways to improve the yield and quality of their food crops such as rice, corn, pulses, potato, and vegetables. There is an urgent need for this in the light of their growing populations depending on the productivity of less and less suitable land. The greatest good the technology could bring is a world free of hunger, but it is no cure against the political and natural disasters which are often the true cause of the problem.

What do you see as the responsibility of the lay public within that debate?

In my view the most important responsibility of the lay public is to maintain their common sense at all times. I would define common sense as the outcome of balancing the good and the bad and choosing what is advantageous to society as a whole. Some NGOs still promote a complete ban on genetic engineering and put the scientist in the role of Dr Frankenstein. I think it is the role of the lay public to refuse such simple-minded representations, to demand a balanced debate, to deny the insult to their intelligence!

Questions for discussion

1. In the interview above, Maarten Jongsma is asked to give both factual description and opinion. Re-read the interview and consider the balance of fact and opinion at different points.
2. What are the values of the scientific community that are stated or implied in his description of how science works? On the basis of this interview and your other sources of understanding, what would you say are ideals that guide natural scientists in their work?
3. Maarten Jongsma says that one of the responsibilities of the lay public is "to demand a balanced debate" on controversial issues within science. To what extent do you consider knowledge of an issue from different points of view to be essential to a sound judgment? To what extent does a judgment involve, in the end, not only facts but values?

Suggested presentation topic

Taking genetic engineering or another controversial area of scientific research as your contemporary issue, consider the responsibilities of the researcher, scientific peers, the lay public, and political decision-makers in the face of new discoveries or technologies that pose ethical questions.

If you are interested in pursuing this topic, you are advised to present it only after the discussions of ethical criteria for judgment later in this chapter. You may wish to do a presentation specifically on the knowledge issues raised by genetic modification in the context of the larger topic of world hunger in Chapter 6.